AD-753 347

TUNABLE PARAMETRIC OSCILLATORS BETWEEN 1.0 MICROMETERS - 5.0 MICROMETERS

Gregory R. Osche
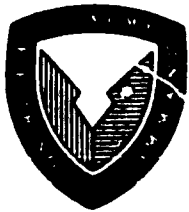
Army Electronics Command
Fort Monmouth, New Jersey

October 1972

Research and Development Technical Report
ECOM-4038

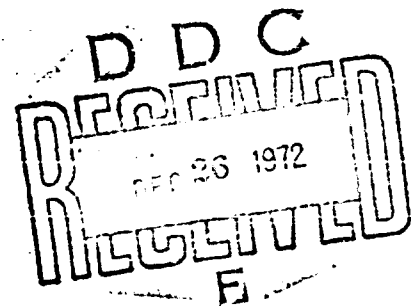**AD753347**

TUNABLE PARAMETRIC OSCILLATORS
BETWEEN 1.0 μm - 5.0 μm

Gregory R. Osche

October 1972

DISTRIBUTION STATEMENT

Approved for public release;
distribution unlimited.

ECOM

UNITED STATES ARMY ELECTRONICS COMMAND · FORT MONMOUTH, N.J.

NOTICES

Disclaimers

The findings in this report are not to be construed as an
official Department of the Army position, unless so desig-
nated by other authorized documents.

The citation of trade names and names of manufacturers in
this report is not to be construed as official Government
indorsement or approval of commercial products or services
referenced herein.

Disposition

Destroy this report when it is no longer needed. Do not
return it to the originator.

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
US Army Electronics Command Fort Monmouth, New Jersey 07703	Unclassified 2b. GROUP

3. REPORT TITLE

Tunable Parametric Oscillators Between 1.0 μm and 5.0 μm

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Technical Report

5. AUTHOR(S) (First name, middle initial, last name)

Gregory R. Osche

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
October 1972	~~18~~ 25	12

8a. CONTRACT OR GRANT NO	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO 1S6 62703 A056	ECOM -4038
c. Task No: 03	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d. Work Unit No: 301	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	US Army Electronics Command ATTN: AMSEL-CT-LE Fort Monmouth, New Jersey 07703

13. ABSTRACT

A general discussion of the practical aspects of continuously tunable parametric down-conversion techniques are discussed. The tuning range of interest is the 1.0 μm - 5.0 μm spectrum, suggesting the use of the 1.06 μm neodymium laser line as a pump. Crystal types, oscillator configurations and design parameters are discussed in a semi-quantitative fashion intended for use by systems engineers and analysts.

I a.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
parametric oscillator						
non-linear crystals						
lasers						
phase matching						
infrared						

TECHNICAL REPORT ECOM - 4038

TUNABLE PARAMETRIC OSCILLATORS BETWEEN 1.0 μm - 5.0 μm

by

Gregory R. Osche

Electro-Optics Technical Area
Combat Surveillance & Target Acquisition Laboratory (ECOM)

October 1972

DA Work Unit No. 1S6 62703 A056 03 301

US ARMY ELECTRONICS COMMAND
FORT MONMOUTH, NEW JERSEY

CONTENTS

FIGURES

Preceding page blank

CONTENTS

INTRODUCTION

Basically there are three non-linear processes for the production of tunable coherent radiation between 1.0 μm and 5.0 μm. These include parametric, Raman and Brillioun interactions. The last two are similar in physical origin, both being a consequence of the modulation of the dielectric constant of the medium by the natural vibrational modes of the medium.[1] The incident electromagnetic radiation is scattered with a frequency shift equal to the characteristic vibrational frequency of the medium. In the Raman effect, scattering from the "optical" modes of vibration causes frequency shifts on the order of several hundred angstroms, whereas, in the Brillioun effect, scattering from the "acoustical" modes of vibration causes frequency shifts on the order of several gigahertz.

Both of these last two interactions are restricted to discrete frequency shifts which are multiples of the natural vibrational modes. In contrast, the parametric process allows for continuous tuning over a bandwidth limited only by the transmission spectrum of the optics and by phase matching requirements.

This paper is intended as a review of existing parametric oscillator designs for the production of tunable radiation between 1.0 μm and 5.0 μm. It is meant to be a general review of the practical requirements in the design and construction of these oscillators and not a detailed analysis of the relevant physics. Ample references are given for the reader who may be interested in a more detailed account.

GENERAL DISCUSSION

The optical parametric frequency converter utilizes the non-linear nature of the induced polarization wave in an optically transparent medium to generate sum, difference, and harmonic frequencies.[2,3] When used in conjunction with an optical cavity tuned to the new wavelengths, resonant enhancement of these new frequencies will occur at the expense of the input frequency or frequencies.[3,4]

Most optical parametric oscillators are designed to operate according to second order theory. That is, the induced polarization wave obeys the relation

$$\vec{P} = \epsilon_o \chi \vec{E} + \vec{P}_{\text{Non-linear}} \tag{1}$$

where

$$(P_{NL})_i = \chi_{ijk} E_j E_k \tag{2}$$

which is second order in the applied fields E_j, E_k. Equation (2) inserted in Maxwells equations allows for energy exchange between three electromagnetic waves, designated as ω_2 - the "pump" wave, ω_1 - the signal wave and

1

ω_3 - the idler wave. These three waves may interact in a variety of ways to yield sum, difference or harmonic frequencies.

In order to make clear just what type of processes may occur, let us define the following terms:

"Difference frequency generation" is simply written as

$$\omega_1 = \omega_2 - \omega_3 \tag{3}$$

where the "pump" wave ω_2 mixes with the "idler" wave ω_3 to yield the difference frequency ω_1, (signal). Of course, the names "signal" and "idler" are interchangeable here, the output beam usually being referred to as the signal. Equation (3) is simply a statement of conservation of energy

$$\hbar \omega_1 = \hbar \omega_2 - \hbar \omega_3 \tag{4}$$

where, from quantum theory, $\hbar$ = PLANCK's constant/2π. Notice that the pump wave at ω_2 must have a greater energy than the signal and idler waves. This means that energy is taken from the pump wave and delivered to the signal and idler waves as the process continues. The signal and idler are present initially in the form of noise. This interaction is also referred to as "down-conversion" since both signal and idler are at a lower frequency. A special case arises when

$$\omega_1 = \omega_3 \tag{5}$$

The equation then becomes

$$\omega_2 = 2\omega_1 = 2\omega_3 \tag{6}$$

This is termed the "degenerate" mode of operation, where the signal and idler have the same frequency. It is also the most efficient form of down-conversion since both the signal and idler are useable as the "output."

For now, let it be stated that this process or interaction will proceed only if the following "phase matching" condition is satisfied within the non-linear crystal;

$$\vec{k}_1 = \vec{k}_2 - \vec{k}_3 \tag{7}$$

where $\vec{k} = \dfrac{2\pi n}{\lambda} \hat{e}$ = wavevector $\tag{8}$

  n = index of refraction

  λ = wavelength

This is simply a statement of conservation of momentum

$$\hbar \vec{k}_1 = \hbar \vec{k}_2 - \hbar \vec{k}_3 \tag{9}$$

in the sense of Equation (4).

Other interactions may take place within the oscillator (parametric) cavity if different phase matching conditions are set up. For example, "sum frequency" generation will proceed if the crystal is so oriented such that

$$\vec{k}_1 = \vec{k}_2 + \vec{k}_3 \tag{10}$$

Here $\omega_1 = \omega_2 + \omega_3$, and now energy must be supplied at both ω_2 and ω_3 for the process to continue. That is, two intense inputs are required. Such a process is referred to as "up-conversion." Notice that if

$$\omega_2 = \omega_3 \tag{11}$$

then

$$\omega_1 = 2\omega_2 \tag{12}$$

which simply corresponds to "frequency doubling."

From the point of view of simplicity and efficiency, up-conversion from the 5.0 μm end of the spectrum is less desirable than down-conversion from the 1.0μm end of the spectrum due to the added requirement of an intense, tunable laser input at the idler frequency in the former case.

Hence, broadband tuning over the 1.0 - 5.0 μm range is most easily accomplished via down-conversion from 1.0μm. This naturally suggests neodymium as the pump source, which has 12 laser lines between 0.9145um and 1.339μm, the well known 1.06μm line being the strongest.[5]

PHASE MATCHING

The requirement for phase matching arises from the dispersive nature of the non-linear media. Basically, since the phase velocity of a light wave is a function of frequency, the "signal," "idler," and "pump" will get out of step "phase wise" with each other as the interaction proceeds, thereby considerably lessening the interaction process. In order to "phase match," one must "index match."[4] This is achieved by taking advantage of the birefringent nature of the crystal,whereby the "pump" wave is made to propagate as an "extraordinary" ray while the "signal" and "idler" propagate as ordinary rays. Other schemes are possible,[3,4] such as the pump and idler being

3

extraordinary rays and the signal as an ordinary ray, but usually tend to lessen the "effective non-linearity" of the medium.

Under these conditions, it is then possible to find a direction of propagation relative to the crystalline axis, which will allow all three waves to have the same phase velocity and, hence, to interact coherently over the full length of the crystal. This leads to a maximum transfer of energy from the pump wave to the signal and idler waves.

As stated previously, the phase matched condition for three wave interactions is defined by the relation[2,3]

$$n_{o1} = \frac{\lambda_1}{\lambda_2} n_{e2}(\theta) + \frac{\lambda_1}{\lambda_3} n_{o3} \tag{13}$$

where n is the index of refraction at the ith frequency, 1, 2, 3 correspond to the signal, pump, and idler wavelengths and o, e representing ordinary and extraordinary rays. The phase matching direction is given by:[4]

$$\cos^2\theta_m = \frac{n_{e2}^{-2}(\theta) - n_{e2}^{-2}}{n_{o2}^{-2} - n_{e2}^{-2}} \tag{14}$$

where θ_m defines the propagation direction relative to the crystalline Z-axis n_e and n_o are principal indicies of refraction of the crystal and $n_{e2}(\theta)$ is defined in the previous equation.

This equation defines a cone of possible phase matched directions about the crystalline Z-axis. The remaining angular coordinate, ϕ is specified by that direction within the crystal which yields the greatest "effective non-linearity."[3] This direction happens to be along the negative crystalline y-axis for LiNbO$_3$ as can be seen in the relation:

$$d_{eff} = d_{15} \sin\theta_m + d_{22} \cos\theta_m (\sin^3\theta - 3\cos^2\theta \sin\theta) \tag{15}$$

where d_{22} is negative.

The actual form of the equation depends on the symmetry of the crystal. In the case of "Barium Sodium Niobate," $Ba_2NaNb_5O_{15}$, we have

$$d_{eff} = d_{15} \sin\theta_m \cos^2\phi + d_{24} \sin\theta_m \sin^2\phi \tag{16}$$

which is essentially independent of ϕ since

$$d_{15} \cong d_{24} \tag{17}$$

Tuning of a parametric oscillator may be achieved either by rotation of the crystal, thereby, changing the phase matching direction, or, by varying the temperature of the crystal, which effects the relative magnitudes of the extraordinary and ordinary[6] indicies of refraction. The phase matching direction, θ_m, is then affected via Equations (14) and (15).

Rotation of the crystal is the most convenient means of tuning, but if large angles are involved it introduces a source of "walk off" for the three beams due to the dispersive nature of the crystal. For large bandwidths, temperature tuning is the most practical and allows for normal incidence to the crystal for all three waves throughout the spectrum. However, it does require the use of an oven having reasonable sensitivity and temperature stability which, ultimately, tends to lessen the overall simplicity and efficiency of the system.

A typical temperature tuning curve for a $LiNbO_3$ down-converter is shown in Figure 1. Notice that a $150^\circ C$ temperature variation allows for tuning between 1.4 and 4.0μm. Approximately $450^\circ C$ variation would be required for the full 1.0μm - 5.0μm range. Figure 1 is representative in form of the tuning curves of most uniaxial crystals, although the actual tuning rates (with temperatures) would be a function of the individual crystal type.

It should be noted that requirements on the crystal oven stability are a function of position on the tuning curve. Near degeneracy, the signal and idler frequencies are quite sensitive to temperature changes, whereas, far from degeneracy they are relatively insensitive to temperature variations.

In point of fact, it is frequently possible to achieve stable oscillations for frequencies far removed from degeneracy and phase matched near room temperature without the aid of an oven.

A more exact discussion of temperature tuning would require specifying the crystal type. Data on the temperature variations of the indicies of refraction of $LiNbO_3$ may be obtained in the references.[6]

THRESHOLD AND EFFICIENCY

The relevant practical aspects of a tunable parametric oscillator are its threshold of oscillation and its conversion efficiency.

The formula for threshold is given by Boyd & Kleinman[3] as

$$P_{TH} = \left\{ \frac{1 + \gamma\xi}{(1 - \gamma^2)^2 (1 - \xi^2)} \right\} \frac{8}{k_3 k} \frac{\epsilon_1 \epsilon_3}{\ell} \frac{1}{h_m(\beta, \xi)} \qquad (18)$$

where

$$\overline{k} = \frac{128\pi^4 f_3^2 d^2}{n_1 n_2 n_3 c^3} = 3.31 \times 10^{-15} \text{ esu} \qquad (19)$$
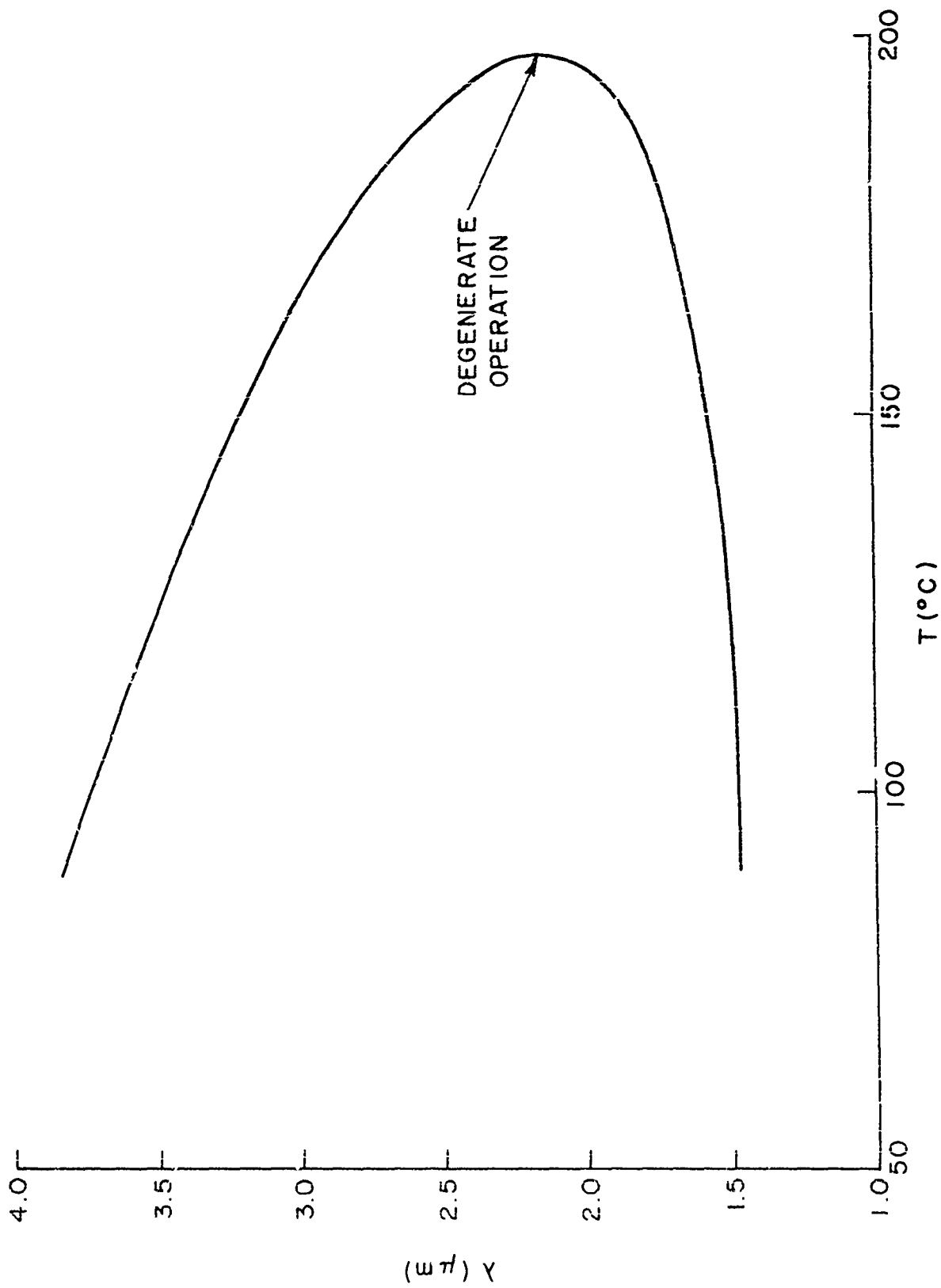
Figure 1. Temperature tuning curve for Lithium Niobate.

$$3 = \frac{\zeta}{2} \left(\frac{\ell\, k_3}{2} \right)^{\frac{1}{2}} = 4.3\ell^{\frac{1}{2}} \tag{20}$$

$$\xi = \frac{2\ell}{k_3\, \omega_o^{\,2}} \tag{21}$$

ℓ = length of crystal

ζ = double refraction angle

The function $\dfrac{1 + \gamma\xi}{(1-\gamma^2)^2 (1-\xi^2)}$ depends on how far from "degenerate" operation

ω_1 and ω_3 are, and is a minimum - equal to unity - at degeneracy. The quantities are the single pass power losses at the signal and idler frequencies, and $k_m(\beta\xi)$ is a complicated expression describing the combined effects of focusing and double refraction. According to the literature, k_m is a near constant[3] varying by no more than 10% from the value of 0.0330 for crystals between 3 mm and 1 cm under optimal focusing conditions.

For one percent losses at the signal and idler, one obtains a threshold for Lithium Niobate of approximately 10 watts. This is very low compared to, say, Raman Conversion which is on the order of 2 megawatts. Mode and phase matching of the laser and oscillator cavities usually raises this value somewhat (50 watts -100 watts) depending on many parameters. This is still low, however, for giant pulse operation or even for repetitively Q-switched operation but tends to make CW operation difficult to achieve. Hence, threshold is not the prime factor to be considered when discussing pulsed parametric oscillators. Of more importance, for large bandwidth tuning is the conversion efficiency as a function of frequency shift.

Consider the energy relation

$$\omega_1 = \omega_2 - \omega_3 \tag{22}$$

or equivalently the momentum relation

$$\vec{k}_1 = \vec{k}_2 - \vec{k}_3 \tag{23}$$

At degeneracy $\omega_1 = \omega_3 = \dfrac{\omega_2}{2}$ so that for a 1.06μm pump, we will obtain 2.12μm signal and idler. As we move away from degeneracy, Equation (22) must still hold (if we are phase matched) so that, if our signal is at, say 3.0μm, the idler will be at (letting $n_1 = n_2 = n_3$ for convenience):

$$\frac{1}{1.06\mu} = \frac{1}{3.0\mu} + \frac{1}{\lambda_3} \tag{24}$$

7

or $\lambda = 1.64\mu m$. Of course, there is nothing sacred about the names signal and idler. One could just as well make the $1.64\mu m$ beam the output "signal" and the "idler" at $3.0\mu m$ simply by changing the oscillator reflectivities. The important thing to consider here is the energy relation, Equation (4), which may be rewritten

$$\hbar \omega_2 = \hbar \omega_1 + \hbar \omega_3$$

This simply means that each pump photon that splits into a signal and an idler photon at frequencies ω_1 and ω_3 does so in proportion to their frequencies. For our example

$$\frac{(Energy)_3}{(Energy)_1} = \frac{\omega_3}{\omega_1} = \frac{\lambda_1}{\lambda_3} = \frac{1.64}{3.0} \sim .45 \tag{25}$$

The energy available at $3.0\mu m$ will be approximately one-half that at $1.64\mu m$ and will comprise only one third of the total energy in all three beams. In general, the greater the frequency shift the less the conversion efficiency by the very fact that it is a single photon process. Of course, if the system design permits use of both the signal and idler as the "output" such as near or on degeneracy, then the overall no-loss efficiency is effectively doubled. It should be noted that although we are considering a "single-photon" process, other multiple photon processes are still present in the form of noise (phase matching prevents amplification of any but the desired interaction). These "higher order" interactions tend to lower the overall efficiency by lessening the number of pump photons available for the desired interaction. However, such effects are minimal when operating well above threshold.

CRYSTALS

There are many parameters to be considered when choosing a non-linear crystal. Some of the more obvious ones are:(1) Optical transparency over the spectrum of interest; (2) A large effective non-linearity; (3) Phase matching capability at reasonable temperatures over the full spectrum of interest; (4) Relatively advanced crystal growing techniques which yield sufficiently large and optically pure crystals;(5) Freedom from water solubility (non-hydroscopic) problems;(6) Curie temperature outside of the phase matching temperature range. There are many crystals which meet some or all of these requirements, and a brief review of these will follow.

Potassium Dihydrogen Phosphate (KDP)

This is one of the earlier crystals used in parametric and second harmonic generation. However, its transmission spectrum is restricted to the 0.22 and 1.5 μm range, is water soluble and has a melting point of 252.6°C. Hence, it is a poor candidate for the 1.0 μm and 5.0 μm spectrum.

LiNbO$_3$ - Lithium Niobate

This material is the most commonly used non-linear material at the present time. Some of its parameters are listed in Table I.

Table I. Properties of Lithium Niobate

Point Group Symmetry	3m
Indicies of Refraction (at 1.0μ, STP)	$n_o = 2.2237$ $n_e = 2.157$
Non-linear Coefficients (relative to d_{36} of KDP)	$d_{31} = 11.9 \pm 1.9 = d_{15}$ $d_{22} = -6.3 \pm 0.6$ $d_{33} = 107 \pm 20$
Transparency	0.4μ – 5.0μ
Curie Temperature	1210°C
Birefringence	Negative Uniaxial
Water Solubility	None

Notice the high Curie temperature, the large transmission spectrum and the lack of any water solubility problems. Also important, is the fact that its non-linear coefficients are approximately 11 times that of d_{36} of KDP. (d_{31} and d_{22} are the relevant non-linear coefficients for LiNbO$_3$. (See Equation (15).) Two other characteristics of LiNbO$_3$ might be mentioned. The material has a tendency to form trapping centers when illuminated in the visible region of the spectrum. However, these effects disappear below 1.0μm. Also, above 550°C the material begins to loose oxygen and discoloration sets in. To prevent this, it is necessary to incorporate an oxygen flow system into the crystal oven. From the systems point of view, this would be quite undesirable, hence the effective tuning range of the crystal would be from 60°C to approximately 500°C. The former temperature is chosen so that the system is always above ambient, obviating the need for a refrigeration system.

According to the previous sections, such a temperature tuning range is more than sufficient to phase match LiNbO$_3$ over the entire 1.0 – 5.0 μm spectrum.

Single crystal LiNbO$_3$ is also available commercially in sizes as large as 1 cm – 1 cm – 2 cm, but at the phase matching angle.

Ba$_2$NaNb$_5$O$_{15}$ – Barium Sodium Niobate ("Banana")

This is a very promising material, having larger non-linear coefficients than LiNbO$_3$. Some of its properties are listed in Table II.

Table II. Properties of Barium Sodium Niobate.

Point Group Symmetry	mm2
Indicies of Refraction (1.06μm STP)	$n_o = 2.262$ $n_e = 2.175$
Non-linear Coefficient (relative to d_{36} of KDP)	$d_{31} = d_{15} = 17 \pm 5$ $d_{32} = d_{24} = 15 \pm 2$ $d_{33} = 21 \pm 2$
Transparency	0.4μm $- 5\mu$m
Curie Temperature	560°C
Birefringence	Negative Uniaxial
Water Solubility	None

Although this crystal has twice the non-linearity of $LiNbO_3$, its major drawback is that it changes from Orthorhombic to tetragonal structure at 300°C and hence its usable tuning range would be restricted to 60°C - 300°C. Other than this, the material is quite promising. Sufficiently large crystals can be grown, although the percentage yield is still less than $LiNbO_3$. Also, the amount of information available in the literature on "Banana" as a down-converter is less than that for $LiNbO_3$.

Ag_3AsS_3 - Proustite

This material has very high non-linear coefficients, as shown in Table III. However, it is rather difficult to grow due to the hazards of arsenic and generally has poor optical quality.

Table III. Properties of Proustite.

Point Group Symmetry	3m
Indicies of Refraction	$n_o = 2.82$ $n_e = 2.58$
Non-linear Coefficients (relative to d_{36} of KDP)	$d_{22} = 50$ $d_{31} = 30$ 0.6μm $- 13\mu$m
Water Solubility	None
Birefringence	Negative Uniaxial

$Sr_{1-x}Ba_xNb_2O_6$ - Strontium Barium Niobate - "Strawberry"

This material has excellent non-linear properties and is transparent between 0.4 μm - 6.0 μm. Its structure is 4 mm. However, it is a poor choice for very broadband parametric tuning because of its low Curie temperature 250°C. There are several ratios of Sr/Ba commercially available, the curie temperature increasing as the Barium content increases. Ultimately, however, one is limited by poor crystalline optical quality at high barium concentrations (minimum Sr/Ba = 0.25).

$BaTiO_3$ - Barium Titanate

This material possesses quite high non-linear coefficients as can be seen in Table IV.

Table IV. Properties of Barium Titanate.

Point Group Symmetry	4mm
Indicies of Refraction	$n_o = 2.437$ $n_e = 2.365$
Non-linear Coefficients (relative to d_{36} KDP)	$d_{15} = d_{14} = 35 \pm 3$ $d_{31} = d_{32} = 37 \pm 3$ $d_{33} = 14 \pm 1$
Transparency	
Curie Temperature	120°C
Birefringence	Negative Uniaxial
Water solubility	None

LiTaO₃ – Lithium Tantalate

This is a very promising material having the following properties (see Table V):

Table V. Properties of Lithium Tantalate.

|	
Structure – Rhombohedral	3m
Indicies of Refraction	$n_o = 2.140$ $n_e = 2.145$
Non-linear Coefficients (relative to d_{36} KDP)	$d_{31} \sim 13$ $d_{33} \sim 56$
Optical Transmission	$0.4 - 4.5\mu m$
Curie Temperature	$610^{\circ}C$
Birefringence	Positive
Water Solubility	None

LiTaO₃ seems to have excellent optical damage characteristics, being two to three orders of magnitude higher than the threshold for LiNbO₃ (25 MJ/cm²). However, little information is available on the phase matching characteristics of the material over the 1.5 – 5.0 μm. It is possible that the small difference between the extra-ordinary and ordinary indicies of refraction would prevent phase matching at any angle for large frequency shifts.

There are many more crystals in which parametric interactions can take place, but all have some major disadvantage such as a restricted tuning range or a low non-linearity. At the present state of the art, LiNbO₃ is generally considered to be the best crystal for large bandwidth tuning.

OSCILLATOR DESIGNS

There are several experimental techniques for achieving optical parametric frequency conversion, which have been discussed in the literature.[4,7,8] Figure 2 shows some of these schemes. Configuration or design is the most basic approach wherein the pump wave is simply injected into the oscillator cavity through the 100% mirror. Although the most popular design, it frequently suffers from severe mirror damage problems at high input pump powers. This is a consequence of the relative difficulty, although technically achievable at the present time, of obtaining good optical quality multilayer dielectric mirror coatings which reflect strongly at the signal and idler wavelengths and transmit at the pump wavelength.[1]

Further, large bandwidth requirements (1.0 – 5.0μm) would require several sets of mirrors (multilayer type) in order to cover the full spectrum. Typically, the higher the reflectivity, the narrower the bandwidth of the mirror so that the 100% oscillator mirrors would be quite restricted in bandwidth, especially if they are doubly resonant.

12

A.

100%   OUTPUT   A   B
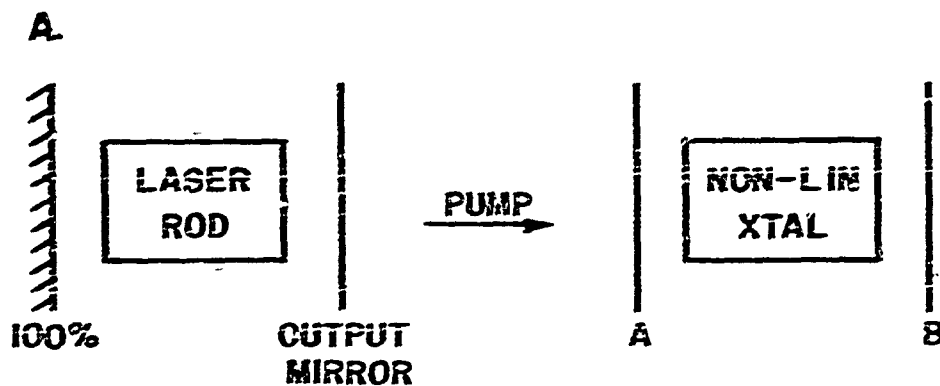
          MIRROR

MIRROR A — 100% AT SIGNAL
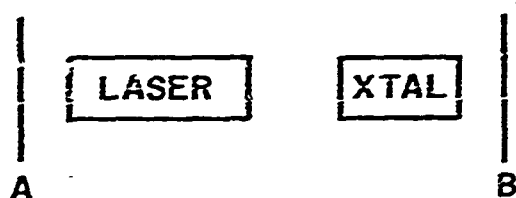
100% AT IDLER

0.00% AT PUMP

MIRROR B — 100% AT IDLER

PARTIAL AT SIGNAL

B.

A   B

MIRROR A — 100% AT SIGNAL

100% AT IDLER

100% AT PUMP

MIRROR B — 100% AT PUMP

100% AT IDLER

PARTIAL AT SIGNAL

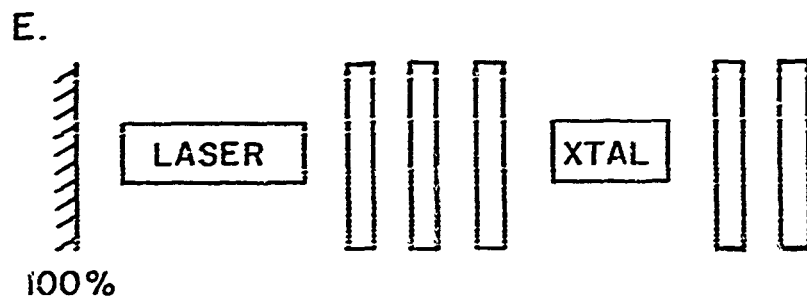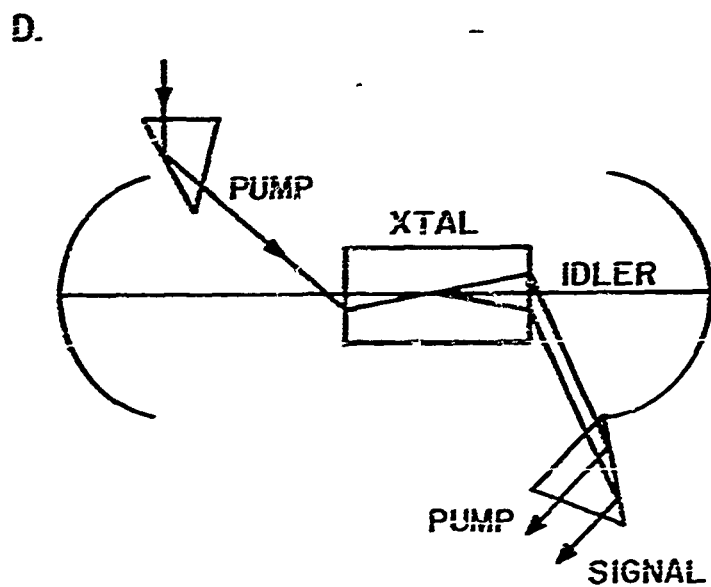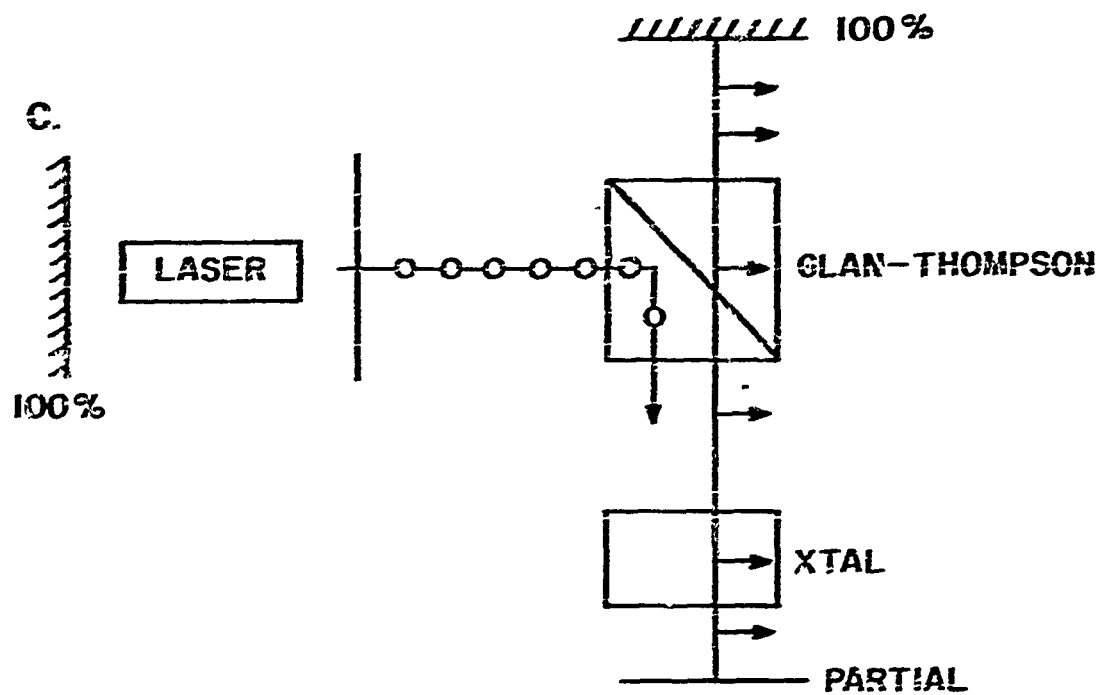Figure 2. Typical device configurations.

13

C.

//////// 100%

LASER

GLAN-THOMPSON

XTAL

PARTIAL

100%

D.

PUMP

XTAL

IDLER

PUMP

SIGNAL

E.

LASER

XTAL

100%

Figure 2. Typical device configurations (continued).

14

Design B eliminates the mirror damage problem at the input by using a common cavity for both laser and oscillator. However, this introduces the added complication of a dispersive and most likely, absorptive material into the oscillator cavity. In fact, such a design is not compatible with Nd: glass or Nd: YAG since the neodymium ion has absorption below 1.35. (It should be remembered that if the signal (or idler) is tuned near the low frequency end of the spectrum (5.0μm), the canonical wave (idler or signal) will approach the pump wavelength (1.06 μm).) (See Figure 1) Hence, a doubly resonant intra-cavity system would be somewhat restricted in bandwidth.

Design C is unique in that it takes advantage of the fact that the signal and the idler waves are orthogonally polarized to the pump wave. A Glan-Thompson prism allows for efficient injection of the pump beam into the oscillator cavity while permitting almost loss free resonance of the signal and idler waves. There is a slight disadvantage here due to the dispersive nature of the prism, which tends to upset the phase and mode matching characteristics of the oscillator cavity. In principle, however, it is quite promising.

Design D is a singly resonant system, meaning only the signal or idler sees a resonant cavity. This approach, introduced by Faulk and Hurrey[8] as a Non-Collinear Oscillator takes advantage of the double refraction properties of the crystal. In general, for such a crystal, the direction of propagation is not the same as the energy flow direction $\bar{S}$ (Poynting Vector), due to the anistropic nature of the medium. Under normal phase matching, $\bar{k}_1$ (signal) $\bar{k}_3$ (idler) and $\bar{k}_2$ (pump) are all collinear or parallel. In the Faulk and Hurrey scheme, $\bar{k}_3$ (idler) and $\bar{S}_2$ (pump) are collinear which allows for a greater interaction length for the energy flow vector $\bar{S}_2$ and $\bar{k}_3$ (idler) (or $\bar{S}_3$ (idler)) since the idler is an ordinary wave, and therefore, $\bar{k}$ and $\bar{S}$ are parallel. Efficiencies up to 46% have been reported using this scheme.

Finally, design E utilizes resonant reflectors in order to obviate mirror damage problems. As is well known, stacked resonant reflectors are simply plane parallel dielectric plates which when illuminated coherently, may yield very high reflectivities (99%) depending upon the index of refraction of the material and the number of plates used. They also have a very irregular reflectivity vs frequency curve which seldom goes to zero anywhere in the spectrum. This results in a high average reflectivity over a bandwidth limited only by the transmission spectrum of the material. Hence, the signal idler and pump may be made to resonate from one reflector throughout the entire tuning range of the oscillator. Moderate broadband coatings of both mirrors could then be used to isolate the two cavities. All of these oscillator designs would require the use of optical materials which are highly transparent over the 1.0μ - 5.0μ spectrum. There are many "window" materials which are transparent in their region, but a large percentage of these are hygroscopic (water soluble) in nature. Sapphire is a non-hygroscopic, extremely hard material which is transparent out to 6.0. It is also anistropic so that consideration must be given to the crystal axis orientation relative to the polarization of the three waves. Of course, zero degree orientation of the C axis relative to the direction of propagation will eliminate any polarization effects. Some properties of Sapphire and other materials, which might be applicable, may be found in Kruse, et al,[9] Harshaw,[10] and Isomet.[11]

Focusing of the pump beam in the crystal is a commonly used technique to raise the power density of the pump. Care must be exercised here, however, so that the power density does not reach the damage threshold of the non-linear crystal. In the case of $LiNbO_3$, this value is generally accepted to be on the order of $(2.5 - 5.0)$ MW/cm^2. A giant pulse laser with a 1 mm mode diameter is already near this value, so that it is usually risky to employ focusing in such systems. However, it may be used advantageously in a high repetition rate, Q-switched system where peak "pump" powers are on the order of one kilowatt. Such fucosing will naturally reduce the total interaction length of the three waves, but this is compensated for by the increased power density of the pump. An "optimum focusing" condition, which involves a compromise between interaction length and focused spot size, is discussed extensively in the literature.[3]

MODE OF OPERATION

A parametric down-converter may be made to follow any mode of operation of the pump laser. These might include the CW, giant pulse or repetitively Q-switched modes. Of course, CW operation is the most difficult to achieve because of the high oscillator threshold, although it is not entirely impractical. Giant pulse operation is the most efficient since the oscillator is working above threshold. Such a device has been designed and built under US Army contract[1] for down-conversion to 1.54 um. Conversion efficiencies on the order of 10% were achieved. This design did not utilize focusing of the pump but rather injected the pump beam directly into the oscillator cavity and crystal. A large $LiNbO_3$ crystal, two centimeters in length,was used to obtain a long interaction path.

High repetition rate (kHz) Q-switched Nd:YAG has also been used as a pump. Here, peak powers on the order of one kilowatt are still far above threshold for the oscillator. Average powers of 40 milliwatts at 2.13 um (degeneracy) have been reported.[12] In this scheme, focusing was accomplished with a 10 cm lens into a 3.5 mm long crystal. The repetition rate was 2 kHz with a peak pump pulse power of 1 kW and a 200 ns pulse half width. An average power conversion efficiency of approximately 10% was obtained.

CONCLUSIONS

Parametric oscillators tunable over the 1.0um - 5.0um spectrum are presently quite feasible. There are no major restrictions on the mode of operation of these devices, so that they are essentially as versatile as the pump laser.

The pump laser may be operated single or multi-mode, Q-switched or CW, and still be compatible with the parametric oscillator requirements. In all cases, however, the pump beam should be polarized so that it satisfies the phase matching requirements most effectively and should not exceed the damage threshold of the crystal. Nd:YAG is the best choice for high repetition rate or CW operation, whereas, Nd: Glass, with its broad 100 Å inhomogenance fluorescent laser line, is the best choice for high power work.

16

Optical components should be transparent throughout the spectrum of interest, non-hygroscopic and with a high resistance to optical damage. Sapphire is a promising choice here. Glass and quartz, the most common materials for optical components, begin to absorb near $3.0\mu m$ and so must be ruled out. Anti-reflection coatings, as well as moderate reflectively coatings, may be utilized over much of the spectrum to optimize the system.

Narrow band, multi-layer dielectric mirrors are not practical to use nor easy to make for such a large tuning range. Instead, braodband resonant reflectors or total internal reflection prisms should be used.

$LiNbO_3$ crystals cast in accordance with phase matching requirements are readily available commercially.

Crystal ovens may also be purchased or designed specifically to match a particular system.

Expected conversion efficiencies are on the order of 10% for small frequency shifts falling off as the ratio of wavelengths for higher shifts. Assuming a pump laser efficiency of approximately 1%, an overall system efficiency of 0.1% at the signal wavelength should be realizable.

REFERENCES

1. R.H. Pantell and H.E. Putoff, "Fundamentals of Quantum Electronics," John Riley & Sons, Inc., New York, N.Y., 1969.

2. N. Bloembergen, "Nonlinear Optics," A Lecture Note and Reprint Volume, W.A. Benjamin, Inc., New York, 1965.

3. G.D. Boyd and D.A. Kleinman, "Parametric Interaction of Focused Gaussian Light Beams," Journal of Applied Physics, Vol. 39, No. 8, July 1968.

4. Ammon Yariv, "Quantum Electronics," 1967.

5. A.K. Levine, "Lasers; A Series of Advances," Vol. I, Marcel Dekker, Inc., New York, p 142, 1966.

6. G.D. Boyd, W.L. Bond, and H.L. Carter, "Refraction Index as a Function of Temperature in $LiNbO_3$," Journal of Applied Physics, Vol. 38, No. 4, March 1967.

7. J.M. Yarborough, J.D. Foster, E.O. Amman, M.K. Oshman, "Down Converter to the Eye-Safe Region," Ecom-0196-F, Final Report, Contract No. DAAB07-69-C-0196. Sylvania Electronics Systems Corp., July 1970.

8. J. Falk and J.E. Murray, "Single Cavity Noncollinear Optical Parametric Oscillation," Applied Physics Letters, Col. 14, No. 8, p 245, April 1969.

9. P.W. Kruse, L.D. McGlauchlin, R.B. McQuistan, "Elements of Infrared Technology; Generation, Transmission and Detection," John Riley & Sons Inc. New York, N.Y., p 139-161, 1963.

10. Harshaw Crystal Catalogue & Brochure. The Harshaw Chemical Company Division of Kewanee Oil Company, Crystal-Solid State Department, 1967.

11. Isomet Corporation, "Optical Crystals," Isomet Corporation, Palisades Park, N.J., 1965.

12. E.O. Ammann, M.K. Oshman, J.D. Foster, and J.M. Yarborough, Applied Physics Letters, Vol. 15, p 131-133, 1 September 1969.